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SUMMARY REVIEW OF NEUTRONIC NOISE TECHNIQUES FOR INCIPIENT BOILING DETECTION IN LIQUID METAL FAST BREEDER REACTORS

by

T. J. Marciniak, L. J. Habegger,
and H. Greenspan

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ABSTRACT

The state-of-the-art of neutronic noise-boiling detection is reviewed as part of an overall effort to determine the feasibility of developing a system for detecting the onset of boiling in proposed sodium-cooled LMFBR cores.

It is concluded that feasibility of a sodium-boiling detector is within the realm of existing technology, but that many problems related to boiling-induced neutron fluctuations, data-gathering, and computer processing of such data, must be resolved before an effective system can be developed.

I. INTRODUCTION

Concern over the possibility of boiling in proposed sodium-cooled fast breeder reactor (LMFBR) cores has prompted an investigation of various systems for detecting incipient boiling (i.e., conditions which could promote boiling) or small amounts of nucleate boiling in the primary coolant. These systems are outlined under Task 4-3.4 of the LMFBR Program Plan.[1] Emphasis is on detection of incipient boiling since at the anticipated high rates of heat transfer (heat fluxes: $\sim 10^6$ Btu/(hr)(ft^2); linear power outputs: 15-20 kW/ft), nucleate boiling could propagate rapidly into gross boiling, with consequent reduction in mass flow rate and heat-removal capacity of the vaporized sodium. Significant vapor-blanketing of a fuel pin or fuel subassembly for more than a few seconds could lead to fuel melting and extensive damage to the core. Thus of equal importance, the response of a detection system must be such that adequate time is available to effect corrective measures before such damage is incurred. The precise time allowed will be studied in other tasks.

Three basic systems for detecting incipient or nucleate boiling are being considered at this time: (1) acoustic, (2) neutronic noise, and

(3) ultrasonic. Of these, only the ultrasonic system is capable of detecting incipient boiling. However, the detector gives local conditions and must be placed in core positions where boiling is most likely to occur. Obviously, if these positions are known, the core can be designed to avoid boiling, thereby eliminating the need for detectors.

The acoustic system does not qualify for detection of incipient boiling, but holds great promise for the detection of nucleate boiling. However, the in-core boiling noise may be partially or completely masked in a background of cavitation noise from pumps and vibrational noise from other primary-system components, or the background noise may be so strong as to completely mask out noise due to small amounts of boiling in the core. What is needed is an alternative method which would be insensitive to noise other than in-core void formation.

One alternative is the neutronic-noise boiling-detection method. This method is based on fluctuations in neutron flux induced by variations in the physical characteristics of the core. These variations may be composed of three components: (1) local thermal effects; (2) formation of sodium void by bubbles; and (3) vibration of fuel pins due to bubble growth and collapse.

The pros and cons of the merits of this method have been expressed by many investigators. For example, Saxe[2] has observed that the effect of bubble void on reactivity in fast reactor cores is position-dependent; that since the sodium-void coefficient is positive near the core center and negative near the outer periphery, there is obviously a position where it is zero; and that boiling at such a position would be difficult to detect. This is a valid observation; however, it still may be possible to detect boiling from reactivity variations due to thermal or vibrational effects, or from variations in the energy spectrum or spatial shape of the neutron flux. A second objection is that since a detector receives neutrons from a significant portion of the core, the effect of nucleate boiling would be "smeared" out, and only large amounts of boiling would be detectable. Still another objection is based on the filtering effect of water reactors in transmitting high frequencies. This effect is diminished in a sodium-cooled fast reactor since the frequency bandwidth is higher by about three orders of magnitude, thus including effects on the power spectrum to about 10 kHz. The latter is higher by an order of magnitude than the frequency expected from growth and collapse of sodium-vapor bubbles in a subcooled liquid.

This report is the result of a study to determine the feasibility of developing a neutronic noise-boiling detection system for the LMFBR Program. The scope of this study was limited to a review of literature on applications of neutronic noise-boiling methods in thermal and fast reactors, sodium-boiling phenomena, instrumentation, mathematical techniques, and related data-acquisition-processing systems.

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This report is the result of a study to determine the feasibility of developing a neutronic noise-boiling detection system for the LMFBR Program. The scope of this study was limited to a review of literature on applications of neutronic noise-boiling methods to the reactor and the sodium-boiling phenomena, instrumentation, mathematical techniques, and related data-acquisition-processing systems.

Briefly, the findings of this review are as follows:

Thus far, the use of neutronic-noise signals for detection of voids, or boiling, in nuclear reactors has been limited to experimental applications to pressurized, water- cooled and moderated, thermal systems. Anamalous noise has been detected and attributed to boiling in these systems, although the evidence in some cases was inconclusive or lacking in alternative means of verification. The suspect nature of these results, combined with physical differences, preclude extrapolation to LMFBRs and emphasize the need for further research. This research should focus on theoretical studies to identify and evaluate all aspects of boiling-induced neutron fluctuations in LMFBRs. These results plus the requirements of the computational procedure will determine the criteria for the data-gathering instrumentation. Finally, development of the required instrumentation will be a prime consideration in evaluating the feasibility of developing a rapid, reliable, neutronic noise-boiling detection system for use in LMFBRs.

II. NEUTRONIC NOISE-BOILING DETECTION IN WATER REACTORS

Many of the papers reviewed in this section also have been reviewed by Saxe.[2,3] This review is by no means complete but, in general, represents the state-of-the-art.

In their experiments on the Thermal Test Reactor, Boyd and Hogan[4-7] reported that it is possible to detect boiling noise provided the boiling occurs near the detector. They avoided spatial effects by wrapping the neutron detector with an electrical heater. Their results showed that the noise caused an increase up to 100 Hz in the power spectral density (PSD).

Colomb and Binford,[8] using an electrical heater and acoustical methods, noted some changes in the PSD of the Oak Ridge Research Reactor. Although they could not conclude that these changes were indicative of boiling, they did recommend further investigation.

Rajagopal and Gallagher[9,10] observed a resonance peak at 13 Hz for the Saxton reactor which they concluded was due to boiling. Their experiments were performed with average coolant temperatures ranging from 526 to 530°F at constant power. The resonance peak was also observed to increase with increasing average coolant temperature. However, no alternative method was employed to ascertain if the peak was attributable to boiling.

Tabor and Hurt,[11] using neutronic-noise techniques and an orificed fuel subassembly, detected a resonance peak at approximately 2 Hz in the

Briefly, the findings of this review are as follows:

Thus far, the use of neutronic-noise signals for detection of voids or boiling in nuclear reactors has been limited to experimental applications to pressurized, water-cooled and moderated, thermal systems. Anomalous noise has been detected and attributed to boiling in these systems, although the evidence in some cases was speculative or lacking in alternative means of verification. The indirect nature of these results, combined with physical differences, precludes extrapolation to LMFBRs and emphasize the need for further research. This research should focus on theoretical studies to identify and evaluate the aspects of boiling-induced neutron fluctuations in LMFBRs. These results plus the recommendations of the computational procedure will determine the criteria for the data-gathering instrumentation. Finally, development of the required instrumentation will be a prime consideration in evaluating the feasibility of developing a rapid, reliable, neutronic noise boiling detection system for use in LMFBRs.

B. NEUTRONIC NOISE-BOILING DETECTION IN WATER REACTORS

Many of the papers reviewed in this section also have been reviewed by Saxe.[5] This review is by no means complete but, in general, represents the state-of-the-art.

In their experiments on the Thermal Test Reactor, Boyd and Tague[7] reported that it is possible to detect boiling noise provided the boiling occurs near the detector. They avoided spatial effects by wrapping the neutron detector with an electrical heater. Their results showed that the boiling caused an increase up to 100% in the power spectral density (PSD).

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Rajagopal and Gallagher[9,10] observed a resonance peak at 18 Hz for the Saxton reactor which they concluded was due to boiling. Their experiments were performed with average coolant temperatures ranging from 525 to 530°F at constant power. The resonance peak was also observed to increase with increasing average coolant temperature. However, no alternative method was employed to ascertain if the peak was attributable to boiling.

Tabor and Hunt,[11] using neutronic-noise techniques and an ordered fuel subassembly, detected a resonance peak at approximately 1.2 Hz in the

Oak Ridge Research Reactor. They estimated that 7.7% of the active region of the subassembly was voided and concluded that bulk boiling, with chugging and flow-reversal, had occurred.

On the other hand, Fry et al.[12] could not find any evidence of nucleate boiling in the Oak Ridge Research Reactor. They concluded that any indication of boiling was probably buried in the coolant-flow noise. However, in the discussion following the paper presentation, one of the spectators (M. A. Schultz) suggested that if the measurements had been extended down to about 0.01 Hz, evidence of boiling may have been found since the possibility of boiling was detected near that frequency in the CP-5 reactor.

Jordan,[13] using a special orificed fuel assembly and PSD measurements of the Ground Test Reactor, was able to reliably detect boiling for a void fraction of $0.014\,\Delta v/v$ per fuel element. The PSD at 1.95 MW indicated a set of pulses of fixed width, frequency, and amplitude because of the multiple-peak structure in the frequency range of 0.2 to 2.5 Hz.

Saxe et al.[14] conducted extensive experiments comparing the relative sensitivity and practicability of acoustic and neutronic-noise methods for the detection of boiling in a swimming pool-type reactor. He concluded that under ideal conditions, i.e., no pump cavitation or flow noise, the acoustic method is about 5×10^4 times more sensitive than the neutron-noise method. Also, because of the high-frequency (>10 Hz) neutronic-filtering effects in water-cooled and -moderated thermal reactors, the data collection time to gain an accuracy comparable to acoustic methods is about 15 times longer for neutron-noise methods,[15] thus significantly reducing the possibility of developing a rapid detection system. Reduced complexity (hence, cost) also was indicated to be an advantage of the acoustic boiling-detection system.

Zwingelstein[16] conducted experiments, similar to those by Saxe, in the swimming pool reactor SILOETTE. Using an electrical heater and the neutronic-noise method, he observed that boiling caused a resonance at about 1-2 Hz.

Fry, Kryter, and Robinson,[17] also using neutronic-noise techniques, were able to detect small amounts of helium void in the Molten Salt Reactor Experiment. The results were reproducible within ±5%; however, the correlation times were quite long.

As evidenced by the referenced experiments, there is considerable variation in the results, even from experiments performed on the same reactor (Oak Ridge Research Reactor). In obtaining the PSD during boiling, some investigators have noted effects at discrete frequencies; others have noted a white noise effect which causes an increase in PSD amplitude at all frequencies. These discrepancies may be due to the fact that most

Oak Ridge Research Reactor. They estimated that 1% of the active region of the subassembly was voided and concluded that bulk boiling, chugging, and flow-reversal, had occurred.

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Jetcer,[12] using a special enriched fuel assembly, and PSD measurements of the Ground Test Reactor, was able to reliably detect boiling for a void fraction of 0.016 vol% per fuel element. The PSD at 1.95 MW indicated a set of pulses of fixed width, frequency, and amplitude because of the multiple-peak structure in the frequency range of 0.2 to 2.5 Hz.

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As evidenced by the referenced experiments, there is considerable variation in the results, even from experiments performed on the same reactor (Oak Ridge Research Reactor). In obtaining the PSD during boiling, some investigators have noted effects at discrete frequencies; others have noted a white noise effect which causes an increase in PSD amplitude at all frequencies. These discrepancies may be due to the fact that most investigators assume that boiling occurs only when the PSD changes, with no verification of boiling by an alternative method. Saxe proposes that the PSD changes at discrete frequencies are due to bulk boiling, or chugging, as was reported by Tabor and Hurt,[11] and the white noise effect is due to the formation and collapse of small bubbles associated with nucleate boiling. In any event, boiling was still inferred only by a change in the PSD, with no alternative means of verification.

Still another explanation may be in the surface condition of the fuel elements. For instance, if the heat-transfer surface is smooth, there will be relatively few nucleation points available for boiling and the boiling would be characterized by the formation of bubbles of about the same size, at a more or less fixed frequency. This could cause a PSD change at only one frequency. However, if the surface is rough, the various-sized nucleation points available could give rise to the white noise effect.

Extrapolation of the foregoing results to boiling detection in liquid sodium would be difficult for two reasons. First, the characteristics of boiling in a relatively low-pressure liquid-metal system are quite different from those in a high-pressure water system. Second, the exact effect of boiling on the PSD of a liquid-metal-cooled reactor is as yet unresolved. However, it may be inferred from the small pressure difference between the bubble and liquid, plus the large superheats experienced in liquid-metal boiling, that the bubbles may be large and cause effects at discrete frequencies.

Saxe rejected the neutronic-noise technique on the basis of experiments which showed that the acoustic method was at least 5×10^4 times as sensitive in a quiet, swimming pool reactor. However, when the circulating pump was turned on, the relative sensitivity decreased by two orders of magnitude. Thus it is conceivable that in a power reactor, with all the potential sources of noise, this relative sensitivity will be reduced even further, perhaps to the point where the neutronic noise method would be more sensitive. In fact, in an LMFBR with superheat of the coolant, the rate of growth and collapse of many small bubbles in a subcooled liquid may not be sufficient to generate a detectable acoustic signal.

III. SODIUM-BOILING PHENOMENA

Because LMFBR systems will be operating at pressures well below those of pressurized water systems plus the large differences in the densities of the vapor and liquid at saturation pressure, it can be expected that should boiling occur, the void formed per bubble will be large. In their experiments, Heineman[18] and others[19,20] observed unstable boiling involving large sodium bubbles at low pressures (≤7 psi), but the instability disappeared as the pressure and heat flux was increased. In LMFBRs, the heat investigators assume that boiling occurs only when the PSD changes, with no verification of boiling by an alternative method. Saxe proposes that the PSD changes at discrete frequencies are due to bulk boiling, or chugging, as was reported by Tabor and Hurt, and the white noise effect is due to the formation and collapse of small bubbles associated with nucleate boiling. In any case, boiling was still inferred only by a change in the PSD, with no alternative means of verification.

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Another phenomenon associated with sodium is the possibility of a significant amount of superheat. This superheat ranges up to several hundred degrees Centigrade and increases as the heat flux increases.[20] It has been pointed out that, for a given situation, the amount of superheat may generate a heat flux greater than burnout.

The amount of superheating is also dependent upon the age of the sodium. Here there is a contradiction between two investigators: Heineman[18] reported that the superheats decrease with increasing age of sodium, whereas Spiller et al.[21] reported an increase. At this time, the work of Spiller et al. is adjudged more reliable, if only based on curves presented in their paper.

Other phenomena of significance have been pointed out by Judd.[22] These include: (1) the channel voiding rate is dependent upon the amount of superheat and not upon the number of bubbles formed, (2) pressures involved in voiding are not high enough to damage the structure, but a high-pressure pulse would be emitted when the vapor bubble collapses in a cooler liquid; and (3) inertial effects are important in liquid-metal bubble growth.

Finally, there is the phenomenon associated with fuel-element rupture when incipient boiling is not present. Ejection and entrainment of fission gas may be detected as possible boiling. This phenomenon also should be considered to ensure the designing of a detector system which is responsive only to sodium boiling.

In summary, incipient boiling in LMFBRs can be expected to be stable, with large voids formed and with superheat of the coolant. The amount of superheat will depend upon the age of the sodium in the reactor, the pressure, and the heat flux. Large pressure pulses will occur when the vapor bubbles collapse; this may not cause local structural damage, but at least will induce motion or vibration of fuel pins. On the other hand, significant vapor blanketing of a fuel pin could result in overheating and ultimate failure of a fuel pin.

IV. ANALYSIS OF REACTOR NOISE

In recent years, there has been a continuing development in the theory and in the application of statistical methods to reactor noise analysis.[17,23-28*] Basic to the analysis, interpretation of experimental data, and planning of

*Also see bibliography in Ref. 29.

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experiments is the mathematical model which is used to characterize the reactor system. Most frequently, the space-independent, monoenergetic-kinetics model with feedback is used. Having collected data, the analysis is generally carried out either in the time domain[29] or the frequency domain,[30] depending upon the particular objective of the data collection.

Thus feasibility of sodium-boiling detection in a fast reactor by neutronic-noise techniques involves reexamination of two main areas: (1) the mathematical model for neutron-density fluctuations from sodium boiling, and (2) methods of acquisition, reduction, and interpretation of the data.

A. Mathematical Model

The selection by Saxe[14] of the acoustic rather than the neutronic-noise method for boiling detection in sodium-cooled reactors was based principally upon an evaluation of experiments using both methods. A more basic approach for evaluating the neutronic-noise methods* is first to identify experimentally and theoretically all existing aspects of neutron-density fluctuations resulting from boiling voids. Next, an optimal situation is assumed in which these fluctuations, superimposed with unavoidable background noise, are completely measurable. This ideal case, with maximum data available, can be postulated as giving the absolute maximum sensitivity. With this sensitivity, the computational procedure must be capable of detecting boiling within specified constraints to justify further consideration of neutronic-noise methods.

If boiling-detection capability is indicated, assuming the absolute maximum sensitivity, consideration must then be given to practical limitations in the ability to measure various quantities. The computational procedure will determine the minimum accuracy to which boiling-induced fluctuations of neutron density must be measured. This will serve as a criterion for evaluating existing instrumentation and identifying what innovations are necessary for boiling-detection applications.

There are several indications of possible boiling-induced fluctuations of neutron density and unavoidable background fluctuations which should be considered in determining the aforementioned absolute maximum sensitivity. The sodium-void reactivity coefficient is one. This coefficient has been investigated both experimentally and theoretically.[31-33] However, it provides indication of the eigenvalue or criticality of the overall system; it does not give information on the perturbation of neutron density as a function of space and neutron energy. Detectors which measure, for example, the difference instead of the average of neutron densities from different locations and energy regions may give significantly increased sensitivity.

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*Approaches to evaluating the acoustic method will not be discussed here.

If studies indicate that spatial effects in boiling-induced perturbations are significant, the spacing of detectors within the core should be carefully considered from the standpoint of spatial attenuation so that the necessary data can be obtained without overburdening the system with detectors and associated instrumentation.

Preliminary experiments have indicated shifts in neutron energy spectra due to the introduction of sodium voids in fast reactor assemblies.[34] Further research is required to identify the importance of these shifts in detecting sodium boiling. One possible method of detecting these shifts is through the use of monitors whose absorbing material composition has been selected to emphasize particular energy regions.

Analytical work has been done on stochastic models[35-38] which include time, space, and energy considerations. Although the systems considered possess simple physical structure and only a one-energy-group bare cube[39] has been implemented for computer calculations, they provide insight and a starting point for further development.

The effect of neutron-density fluctuations indirectly due to boiling also must be evaluated, e.g., material temperature variations, pressure variations, and structural vibrations. In addition to the relative magnitude of the disturbance from these sources, the time sequence in which these events occur is important in determining whether they will influence the boiling-detection scheme. Studies of the time sequences have been reported,[40] but results are questionable because of the uncertainty in the nature of void formation in boiling sodium.

The whole-system computer programs[41,42] used in safety analysis can be modified to study the interrelationship between the neutronic and nonneutronic aspects.

Another theoretical approach is to find the reactor-response function by successive determination of the kernels in the functional expansion of the reactor output subject to a stochastic input.[43] This would then be the analogue of the impulse response of a linear system.

In a power reactor, unavoidable background noises originate from two sources: (1) the random nature of the neutronics, and (2) the various mechanical and thermohydraulic oscillations associated with the coolant flow. The first source can be approximated theoretically,[44-46] but the second may require experimental measurement in addition to theoretical estimation because of the complexity of coolant flow systems. In this case, extrapolation of background measurements on prototype LMFBRs such as the EBR-II, FERMI, and FFTF systems may be useful.

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The effects of background noise in instrumentation also must be considered in the final analysis, but these effects are of lesser importance because of their possible cancellation in multidetector correlation techniques.

B. Methods of Data Acquisition, Reduction, and Interpretation

In all cases, detector signals are transformed into a form consistent with the method of data processing employed and serve as input to a digital computer. Whatever the method, the detector efficiency and cycle of data acquisition and processing must be such that sufficient time is available to effect corrective action on the reactor, should anomalous behavior be predicted.

To circumvent the problem of detector efficiency, use of two-detector cross-correlation techniques[25,26] seems to be indicated.

Use of on-line digital computers to speed data reduction and analysis is postulated. Such computers have been used in reactor noise experiments,[47,48] and applicability to reactor control also has been studied.[49,50]

The time required for the collection and analysis of data to provide sufficient boiling-detection information is dependent on various system parameters which are presently unknown. However, order-of-magnitude estimates can be made, based on present knowledge. An optimistic calculation can be based on an assumption that neutronic boiling noise contains a power spectrum with components up to 1000 Hz and that a bandwidth of 100 Hz provides sufficient resolution to distinguish the neutronic boiling noise from other noise components. With these assumptions, an absolute minimum sampling time of 0.005 sec at a sampling rate of 2000/sec is required; but to provide sufficient statistical accuracy, a required total sampling time of ~0.5 sec can be expected for a total of 1000 data points.[51] Use of the Fast Fourier Transform algorithm to process the 1000 data points requires approximately 0.1 sec, assuming 10 μsec per arithmetic operation.[48] A more pessimistic approximation, again based on an upper frequency of 1000 Hz but assuming a bandwidth of 5 Hz, requires a total sampling time of ~10 sec, with a sampling rate of 2000/sec. Fast Fourier Transform analysis of this data requires approximately 3 sec at 10 μsec per arithmetic operation.[48]

Computations based on polarity-correlation techniques, with improvements[47,52] to increase data-collection efficiency, permit rapid determination of covariances, at least for cases where the probability distribution functions for the sampled functions are known.[52,53] If the response function is determined by pulsing the reactor with a known special random input,[43] then covariances again can be calculated directly.

The effects of background noise in instrumentation also must be considered in the final analysis, but these effects are of lesser importance because of their possible cancellation in multidetector correlation techniques.

E. Methods of Data Acquisition, Reduction, and Interpretation

In all cases, detector signals are transformed into a form consistent with the method of data processing employed and serve as input to a digital computer. Whatever the method, the detector efficiency and cycle of data acquisition and processing must be such that sufficient time is available to effect corrective action on the reactor, should anomalous behavior be predicted.

To circumvent the problem of detector efficiency, use of two-detector cross-correlation techniques[21,22] seems to be indicated.

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Computations done during the early design stages, supplemented by on-line noise calculations during the startup period, could provide case histories of the effect of components on neutron fluctuations in the reactor. On the basis of these histories, criteria could be developed, stored in a computer, and used to evaluate conditions conducive to anomalous behavior in future core concepts.

V. DETECTOR CRITERIA--STATE-OF-THE-ART

A. Criteria

A vital consideration for determining the feasibility of using neutron-noise analysis for boiling detection in LMFBRs is the availability of neutron detectors which satisfy certain performance criteria. These criteria will be established by (a) the data requirements of the analytical procedure, (b) the nature of the neutron flux being monitored, and (c) the environment in which the detector must operate. It can be assumed that, as a minimum, the detectors must satisfy the tentative criteria outlined in the LMFBR Program Plan.[1] These criteria are listed in Table I.

TABLE I. Tentative Criteria for LMFBR Neutron Detectors

	In and Near Core	Out of Core
Diameter	≤1/4 in.	
Temperature		
Range	300-1400°F	300-1400°F
Steady-state maximum	1400°F	1200°F
Transient	to 2000°F	1400°F
Thermal shock		
Maximum rate	100°F/sec for 3 sec	100°F/sec for 3 sec
Maximum change	600°F in one min	600°F in one min
Immersion depth	to 50 ft	to 50 ft
Thermal cycling	as determined by study	
Gamma tolerance	to 10^9 R/hr	to 10^8 R/hr
Sensitivity		
Counters	10^{-5}-10^{-10} cps/nv	>0.7 cps/nv
Current chambers	10^{-15}-10^{-19} A/nv	$>10^{-14}$ A/nv
Lifetime	1 year at 10^{15} nv	>1 year
Neutron flux	10^{11}-10^{16} nv	
Range	2 or more decades	

Size of the detector becomes an important consideration if it is to be located in or near the core. In general, miniaturization is obtained at the sacrifice of sensitivity.

The detector, cables, and other accessory instrumentation must be capable of withstanding the adverse environmental conditions of high temperature, thermal shock, thermal cycling, possible sodium immersion, and high radiation fields. The transient response required is related to the frequency range of the neutron-fluctuation power spectrum which is of interest.

An efficient method of gamma discrimination may be required to reduce background noise due to the high gamma fluxes.

Detector sensitivity is a function of the yet unknown nature of the neutron fluctuations induced by sodium boiling, the magnitude of the instrumentation noise, and the data-analysis procedure. For example, a lower signal-to-noise ratio may be acceptable, using cross-correlation between detectors. Increased efficiency in measuring boiling-induced neutron fluctuations may be achieved by selective weighting of particular regions of the neutron-energy spectrum. Spectrum weighting is achieved by proper choice of absorber materials in the detector.

Detectors for operation in the current mode are principally for neutron monitoring at high powers, whereas counting modes are for low powers or startup applications. No need has been indicated for incipient boiling detection at low powers, where the counting mode is applicable.

Lifetimes of the detectors must be long enough so as not to require frequent reactor shutdown to effect their replacement. The lifetime specified in Table I may be achieved by using transversing or retractable detectors.

B. State-of-the-Art

The following is a summary review of the state-of-the-art of neutron detectors in terms of satisfying the criteria listed in Table I. More comprehensive reviews have been published elsewhere.[54,55]

Of the various types of neutron detectors available or under development, ion chambers and self-powered detectors show the greatest potential for application in LMFBRs. Ion chambers containing either boron or fissile material are both being considered, although the latter type holds promise for a wider range of applications. The $1/v$ cross section of boron limits the boron-containing detector to measurements of thermal flux. On the other hand, detectors containing fissile material can be designed to weight

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Ionization chambers with diameters as small as 0.05 in. have been manufactured for maximum temperatures lower than required for LMFBR applications. Thus miniaturization for in-core use is feasible. However, loss of sensitivity accompanying miniaturization may make large out-of-core detectors or banks of detectors[60] more attractive for neutron-fluctuation analysis.

At the anticipated high-flux levels in or near the core during power operation, the ratio of neutron to gamma fluxes makes the gamma-induced portion of the detector current output relatively unimportant.[55] At low- and intermediate-power levels, however, this gamma-induced current becomes significant; it can be removed by using a compensated current chamber or, in the case of fission chambers, by pulse-height discrimination.

Response time, sensitivity, and gamma discrimination of ionization detectors are determined largely by the spacing between electrodes, gas type and pressure, and coating thickness.[55] These design parameters must be optimized in view of the signal requirements for boiling detection.

Present designs of fission and boron ion chambers are rated for operation up to 1200°F. Further development and testing is required to ensure compatibility with the LMFBR environment.

Self-powered detectors are attractive because of their inherent small size and elimination of the need for a high-voltage supply.[61-64] Also, elimination of the gas volume, sensitive coating, and fragile center wire needed in ion chambers make this type of detector inherently rugged. Self-powered detectors are presently in use in water reactors; however, their use in the more adverse LMFBR environment is contingent upon further development.

Other types of detectors may receive more attention in the future, depending on the need and the progress in their development. The neutron thermometer is one example. It is small and rugged, and the fissile composition can be varied for selective energy-spectrum weighting; however, calibration is made difficult by a dependence on environmental temperature.[65-67] Solid-state detectors[68] are another example. They are small and have fast time responses, but basic improvement is necessary for application to high neutron- and gamma-flux environments. Gamma monitors are expected to have limited capabilities because of high sodium and fission-product background activities.

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VI. CONCLUSIONS

On the basis of this survey, it is concluded that further theoretical and experimental research is required to demonstrate the feasibility of neutronic-noise techniques for detection of boiling in LMFBRs.

The bulk of the literature on neutronic noise-boiling detection is based on experimental applications to water-cooled, thermal reactors. Several researchers have detected anomalous noise which they attributed to boiling, although the evidence in some cases was inconclusive. Discrepancies have also appeared in the various reported results. Extrapolation of these results to LMFBRs is further complicated by the differences between the two types of reactor systems. For example, the frequency-filtering effect of an LMFBR is less than that of a thermal water reactor. Also, the boiling bubbles in low-pressure liquid metals are likely to be much larger than in high-pressure water. Further research is required to determine the nature and importance of these differences.

In view of the inadequacy of the available information, it is recommended that an evaluation of the maximum sensitivity of neutronic methods of boiling detection in LMFBRs be initiated using a more basic approach. This approach should rely heavily on theoretical studies to identify and evaluate all aspects of boiling-induced neutron fluctuations, including fluctuations in energy spectrum and spatial shape.

With regard to data acquisition and processing, more recently developed methods of statistical data analysis, such as fast Fourier transform algorithms, cross-correlation, and polarity correlation should be explored because of their potential in decreasing computational times.

Theoretical identification of the nature of boiling-induced neutronic noise plus the data requirements of the computation procedure will determine the criteria for the data-gathering instrumentation. Evaluation of the feasibility of developing the required instrumentation will be a prime consideration in evaluating the feasibility of neutronic noise-boiling detection.

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